

A new contribution to the conventional atmospheric neutrino flux

Thomas K. Gaisser

*Bartol Research Institute and Dept. of Physics and Astronomy
University of Delaware, Newark, DE, USA*

Spencer R. Klein

*Lawrence Berkeley National Laboratory, Berkeley, CA, USA and
University of California, Berkeley, Berkeley, CA, USA*

Abstract

Atmospheric neutrinos are an important background to astrophysical neutrino searches, and are also of considerable interest in their own right. This paper points out that the contribution to conventional atmospheric ν_e of the rare semileptonic decay of K_S becomes significant at high energy. Although the $K_S \rightarrow \pi e \nu$ branching ratio is very small, the short K_S lifetime leads to a high critical energy, so that, for vertical showers, the inclusion of K_S semileptonic decay increases the conventional ν_e flux by $\approx 30\%$ at energies above 100 TeV. In this paper, we present calculations of the flux of ν_e from K_S . At energies above their critical energies, the ν_e fluxes from kaon decay may be simply related to the kaon semileptonic widths; this leads to a near-equality between the flux of ν_e from K^+ , K_L and K_S .

Keywords: Atmospheric neutrinos, Neutrino astronomy, neutral kaons

1. Introduction

Atmospheric neutrinos are of interest for understanding cosmic-ray interactions in the atmosphere and as probes of physics, such as neutrino oscillations [1, 2]. They are also an important background in searches for high-

Email addresses: gaisser@bartol.udel.edu (Thomas K. Gaisser),
srklein@lbl.gov (Spencer R. Klein)

energy astrophysical neutrinos, particularly in searches for a diffuse flux. In diffuse searches, the significance of any signal depends critically on the assumed flux and spectral shape of the atmospheric neutrino background.

High-energy atmospheric neutrinos are typically divided into two classes: conventional and prompt [3]. Conventional neutrinos come from the decays of pions and kaons, and the muons produced when pions and kaons decay. Pions and kaons have lifetimes long enough so that, at energies above ≈ 1 TeV, they are likely to interact before they decay; the relative interaction probability increases linearly with energy, so the neutrino spectrum from decays at high energy is softer. At high energies, where most muons reach the ground before they decay, the principal sources of ν_e are the decays $K^+ \rightarrow \pi^0 e^+ \nu_e$ and $K_L \rightarrow \pi^- e^+ \nu_e (\pi^- e^- \bar{\nu}_e)$. It was pointed out recently that η and η' can decay to $\mu^+ \mu^-$ and contribute to the conventional muon flux, but not to the neutrino flux [4].

Prompt neutrinos come from the decays of charmed and bottom hadrons. These particles decay quickly (critical energies $\sim 10^7$ GeV or higher) so the spectral index of neutrinos from their decays is similar to that of the primary cosmic-ray spectrum in the energy range considered here.

There have been many calculations of the conventional neutrino flux. Several analytic calculations exist, mostly using the method of Z-moments [3, 5]. Other calculations use Monte Carlo simulations, often based on different hadronic interaction models [6, 7, 8].

In this work we evaluate the contribution of the rare, semileptonic decay of K_S to the flux of ν_e . This contribution has been neglected previously because of its low branching ratio, which makes its contribution negligible below 10 TeV. For the same reason, this channel is not tracked in CORSIKA [9]. Although the semileptonic branching ratio is very small, the K_S lifetime is very short, so that, in cosmic-ray air showers, it is more likely to decay than to interact. As a consequence, its contribution to the flux of ν_e is one power harder in energy than those from K_L and K^\pm , so that at sufficiently high energy it contributes a significant fraction of the total.

2. Electron neutrinos from K_S

The characteristic energy ϵ_i that characterizes whether an unstable particle is more likely to interact or decay in the atmosphere is

$$\epsilon_i = \frac{m_i c^2 h_0}{c \tau_i}, \quad (1)$$

Type	Mass (MeV)	Br($K \rightarrow \pi e \nu$) (%)	Lifetime (s)	Characteristic energy (GeV)
K^+	493.6	5.04	1.24×10^{-8}	850
K_L^0	497.6	40.55	5.12×10^{-8}	210
K_S^0	497.6	0.07	0.90×10^{-10}	120,000
Charm	≈ 1800		$\approx 10^{-12}$	$\approx 4 \times 10^7$

Table 1: Masses, semi-electronic branching ratios, lifetimes and characteristic energy for the different kaon types, and, for comparison, charmed hadrons [10, 11].

where m_i and τ_i are the particles mass and lifetime, and h_0 is a scale height in the atmosphere, typically 6400 m [3]. The energy at which hadronic interactions become important depends on the atmospheric density, which varies with zenith angle θ_z . Interactions become predominant at energies above the critical energy:

$$E_{\text{crit}} = \epsilon / \cos(\theta_z) \quad (2)$$

If the particle energy is higher than E_{crit} , then it is likely to interact before it can decay. Below the critical energy for a given channel, the spectrum of neutrinos from kaon decays closely matches that of the cosmic-ray spectrum, roughly $dN/dE \approx E^{-2.7}$, with the neutrino taking an average of roughly 25% of the kaon energy for $K \rightarrow \pi e \nu$ decays. At energies above the critical energy, the increasing interaction probability softens the spectrum by E^{-1} , to $dN/dE \approx E^{-3.7}$. Table 1 shows the semi-electronic branching ratios and critical energies for different types of kaons, along with those of charmed hadrons for comparison.

The ν_e flux from K_S decay may be easily determined by reference to the ν_e flux from K_L decays. K_S and K_L are produced at the same rate in air showers, and the $K \rightarrow \pi e \nu_e$ kinematics are almost identical. At low energies, the K_S contribution to the atmospheric ν_e flux is small, reduced by the ratio of the branching ratios K_S/K_L : $0.07/40.55 = 0.0017$. At higher energies, above $210 \text{ GeV} / \cos(\theta_z)$, the spectrum of ν_e from K_L -decay softens to $E^{-3.7}$, while the spectrum of ν_e from K_S remains unchanged. Thus, the relative ν_e contribution increases linearly with the energy. At the K_S critical energy of $120 \text{ TeV} / \cos(\theta_z)$, the ratio has increased by $\epsilon_{K_S}/\epsilon_{K_L} \approx 588$, and the K_S and K_L contributions to the ν_e flux are equal! This is not just a fortuitous numerical coincidence. It happens because the lifetime is inversely related to the total decay width, and the branching ratio is the ratio of the semileptonic

width to the total width. With $\epsilon \propto 1/\tau = \Gamma_{tot}$ and $Br(K \rightarrow \pi e \nu) = \Gamma_{sl}/\Gamma_{tot}$, as long as the K_S and K_L are produced in equal numbers, the ratio of the ν_e fluxes for neutrino energies above the two E_{crit} is

$$\begin{aligned} \frac{\phi(\nu_e \text{ from } K_S)}{\phi(\nu_e \text{ from } K_L)} &= \frac{Br(K_S \rightarrow \pi e \nu) \epsilon_{K_S}}{Br(K_L \rightarrow \pi e \nu) \epsilon_{K_L}} \\ &= \frac{\Gamma_{SL}(K_S)/\Gamma_{Tot}(K_S) (1/\tau_{K_S})}{\Gamma_{SL}(K_L)/\Gamma_{Tot}(K_L) (1/\tau_{K_L})} = 1. \end{aligned} \quad (3)$$

A similar argument applies for $K^+ \rightarrow \pi^+ e \nu_e$, which has a similar mass and semileptonic width as the K_L and K_S . However, associated production in reactions like $pp \rightarrow K^+ \Lambda p$ is different for K^+ than for the K^0 and \bar{K}^0 from which the K_L originate. As a consequence, the contribution of charged kaons to the flux of ν_e is not exactly equal to that of K_L .

Neglecting for the moment associated production, at energies $E_\nu > E_{crit}$, the inclusion of K_S increases the ν_e flux by about 50%. For quasi-vertical angles of incidence, this increase occurs at energies of ≈ 100 TeV, which is the range in which most current searches for extra-terrestrial neutrinos are focused. At higher energies, the enhancement is large for a wider angular range, but the conventional ν_e flux is overshadowed by the prompt flux.

A similar enhancement occurs for ν_μ , via $K_S \rightarrow \pi \mu \nu_\mu$. However, because of the large ν_μ contribution from two-body decays of charged kaons and pions, it is much less significant. Figure 7 of [4] gives the relative contribution to ν_μ production of π^+ , K^+ , K_L and μ decay. K^+ decay dominates at energies above 500 GeV; the contribution from K_L is negligible, so, at higher energies, the K_S contribution will remain small.

There are additional ν_e contributions from the semileptonic decays of strange baryons like the Λ and Σ ; some of these baryons have semileptonic branching ratios similar to that of the K_S . However, their production rates are lower, and the neutrino carries only a relatively small fraction of the incident baryon momentum. So, their contribution to the total flux should be small.

3. Flux calculations

We extend the flux calculation described in Ref. [11] to include the contribution of $K_S \rightarrow \pi e \nu_e$. The calculation is a generalization of the scaling solutions of the coupled cascade equations for hadronic cascades in the atmosphere [3] in which the spectrum weighted moments are allowed to depend

on energy in order to take account of the non-power-law behavior of the primary spectrum (the knee). The Z-factors for production of charged kaons, for example, are generalized to

$$Z_{NK^\pm}(E) = \int_E^\infty dE' \frac{\phi_N(E')}{\phi_N(E)} \frac{\lambda_N(E)}{\lambda_N(E')} \frac{dn_{K^\pm}(E', E)}{dE}. \quad (4)$$

Here $\lambda_N(E)$ is the nucleon interaction length, dn_{K^\pm} is the number of charged kaons produced in dE by nucleons of energy E' , and $\phi_N(E)$ is the spectrum of nucleons. This method was proposed in Ref. [12], and is a good approximation if the energy dependences are smooth. Simple forms for the hadronic cross sections [13] are used to interpolate and extrapolate tabulated values [3] of the spectrum weighted moments. For the calculation of the neutrino fluxes the spectrum of nucleons per GeV/nucleon is needed, assuming validity of the superposition approximation in which bound nucleons produce mesons as if they were free. We use the spectrum of nucleons from Model H3a of Ref. [14].

The basic equation for the flux of $\nu_e + \bar{\nu}_e$ at sufficiently high energy so that the contribution from muon decay can be neglected ($> \sim 1 \text{ TeV}/\cos\theta$) is

$$\begin{aligned} \phi_\nu(E_\nu) = \phi_N(E_\nu) \times \left\{ \frac{Z_3 b_{K^+e3}(Z_{NK^+} + Z_{NK^-})}{1 + B_3 \cos\theta E_\nu/\epsilon_K} \right. \\ + \frac{Z_3 b_{K_Le3} Z_{NK_L}}{1 + B_3^* \cos\theta E_\nu/\epsilon_{K_L}} \\ \left. + \frac{Z_3 b_{K_Se3} Z_{NK_S}}{1 + B_3 \cos\theta E_\nu/\epsilon_{K_S}} \right\}. \end{aligned} \quad (5)$$

Here $Z_3 \approx 0.134$ [5] is the spectrum-weighted moment for the K_{e3} decay at low energy (when $E_\nu \ll \epsilon_{K_x}$). The branching ratios b_{K_xe3} are for each kaon flavor to the K_{e3} mode, and Z_{NK_x} is the spectrum weighted moment for a nucleon to produce a kaon of type x . The denominator interpolates between the low and high-energy behavior, where low and high are defined relative to ϵ_{K_x} for each neutrino source. Explicitly,

$$B_3 \approx \frac{0.134}{0.061} \left(\frac{\Lambda_K - \Lambda_N}{\Lambda_K \ln \frac{\Lambda_K}{\Lambda_N}} \right) = \frac{Z_3}{Z_3^*} \left(\frac{\Lambda_K - \Lambda_N}{\Lambda_K \ln \frac{\Lambda_K}{\Lambda_N}} \right) \quad (6)$$

where $Z_3^* \approx 0.061$ [5] is the high energy value of the spectrum weighted moment for K_{e3} when the factor ϵ_{K_x}/E weights the decay by an extra power

of $1/E$. Z_3 and Z_3^* account for the fraction of the kaon momentum carried by the neutrino. The branching ratios and critical energies are listed in Table 1. The factor

$$\left(\frac{\Lambda_K \ln \frac{\Lambda_K}{\Lambda_N}}{\Lambda_K - \Lambda_N} \right)$$

in Eq. 6 arises from the integral over atmospheric depth of the kaon spectrum multiplied by the probability of meson decay in the high-energy limit,

$$\sim \int \frac{dX}{\lambda_K} \frac{\epsilon_{Kx}}{E_\nu \cos \theta X} (e^{-X/\Lambda_K} - e^{-X/\Lambda_N}). \quad (7)$$

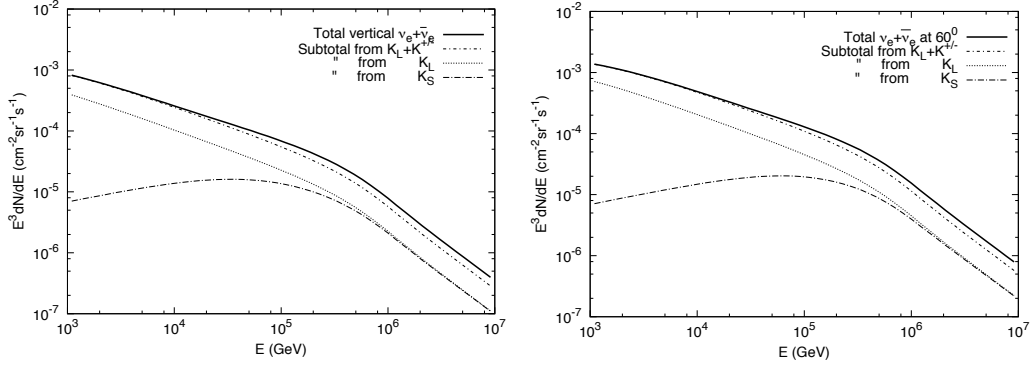


Figure 1: Electron neutrino flux showing the contribution of K_S separately. Left: vertical; Right: 60° .

We use a set of Z-factors described in the Appendix to evaluate the fluxes of electron neutrinos from Eq. 5. Results for the flux of $(\nu_e + \bar{\nu}_e)$ at two zenith angles are shown in Fig. 1. Figure 2 illustrates how the fractional contribution of K_S evolves with energy at different zenith angles. The critical energy for K_S is $\approx 120 \text{ TeV}/\cos \theta$, and the neutrino flux from K^\pm and K_L increases significantly toward the horizontal. As a consequence, when the flux is averaged over zenith angle, the onset of the saturation of the K_S contribution is delayed by an order of magnitude to $E_\nu \sim 1 \text{ PeV}$.

The K_L and K_S states are not directly produced in hadronic interactions. Instead they are rotations of $K^0 = (d\bar{s})$ and $\bar{K}^0 = (\bar{d}s)$. Between production and decay, the $K^0 = (d\bar{s})$ and $\bar{K}^0 = (\bar{d}s)$ states mix through the mass eigenstates K_S and K_L . The probability for a neutral kaon to interact or

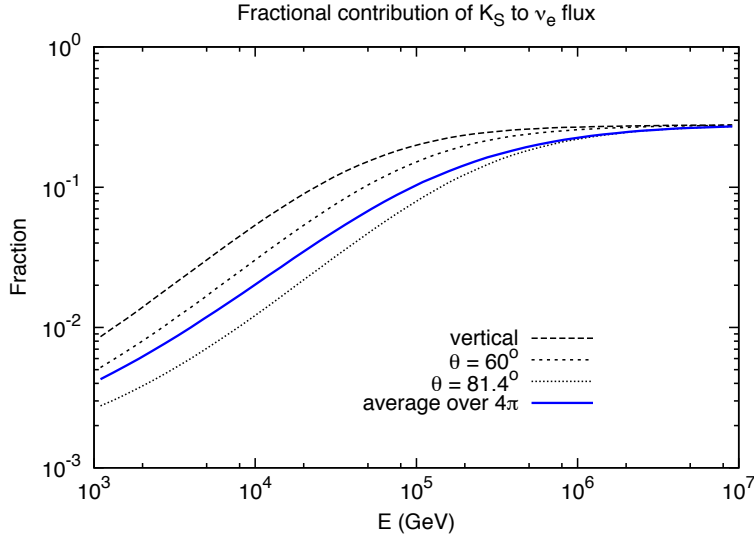


Figure 2: Fractional contribution of K_S to the flux of ν_e at several zenith angles and averaged over all directions.

decay as $K^0 \rightarrow \pi^0 e^+ \nu_e$ or $\bar{K}^0 \rightarrow \pi^0 e^- \bar{\nu}_e$ at a later time is given by the probability to find the system in one state or the other. When the states are fully mixed, equal numbers of ν_e and $\bar{\nu}_e$ are produced in the Ke3 decays of K_L . In the high energy limit, however, when the neutral kaons interact before they are fully evolved, then asymptotically the relative number of ν_e and $\bar{\nu}_e$ reflects the relative importance of $K^0 \rightarrow \nu_e$ and $\bar{K}^0 \rightarrow \bar{\nu}_e$ at production just as the neutrinos from decay of charged kaons reflect the relative production of $K^+ \rightarrow \nu_e$ and $K^- \rightarrow \bar{\nu}_e$. Regeneration of K_S when neutral kaons interact in the atmosphere may also affect the flux of neutrinos.

The effects of kaon oscillations in the cascade equations from which Eq. 5 follows can be approximately accounted for by reference to the standard treatment of kaon oscillation in Ref. [15]. The oscillation frequency is determined by the K_L - K_S mass difference $\Delta = m_{K_L} - m_{K_S} = 0.592 \times 10^{10} \text{ s}^{-1}$ [10]. Thus the oscillation period is $t^* \approx 1.7 \times 10^{-10} \text{ s}$. Whether the neutral kaons are more likely to interact before or after the oscillations are fully evolved depends on the structure of the atmosphere in the same way as the competition between decay and interaction. As a consequence, the transition between the two regimes is given by a formula like Eq. 1 with τ_i replaced by $t^* \approx 2.1\tau_S$.

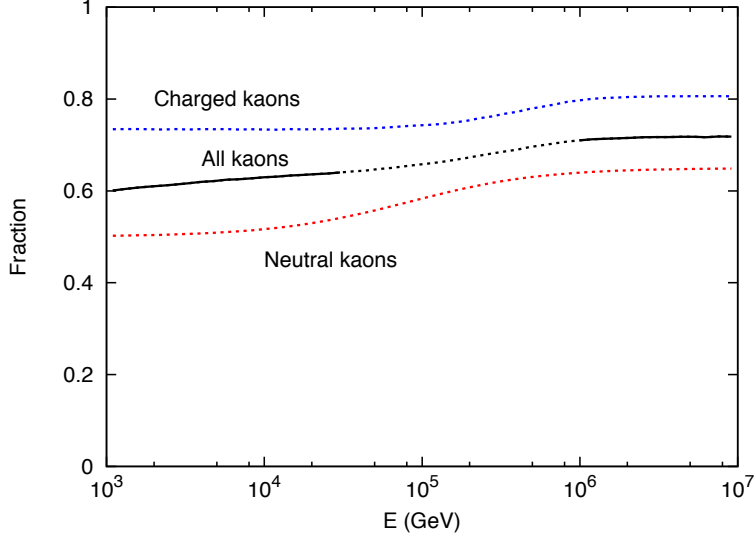


Figure 3: Fraction of atmospheric ν_e in the total flux of $\nu_e + \bar{\nu}_e$. The fractions are shown separately for charged kaons (top/blue), neutral kaons (bottom/red) and all kaons.

The characteristic $\epsilon_{\text{osc}} \approx 56$ TeV is fortuitously close to the critical energy for K_S of 120 TeV. At higher energies the decays reflect the excess of K^0 over \bar{K}^0 at production.

For electron neutrinos from Ke3 decays of charged kaons we expect approximately 74% ν_e and 26% $\bar{\nu}_e$ at all energies. This estimate follows from the values of the respective Z-factors and the relative abundance of protons and neutrons in the primary spectrum of nucleons (see Appendix, Eq. 12). Decays of K_L give equal numbers of neutrinos and antineutrinos at low energy. For $E_\nu > \epsilon_{\text{osc}} \approx 50$ TeV, however, the ratio increases, because the decays of neutral kaons still reflect the excess of K^0 over \bar{K}^0 at production. From the numerical approximations of Z_{K^0} and $Z_{\bar{K}^0}$ in the Appendix, we estimate that the asymptotic ratio is approximately 65% to 35% in favor of ν_e . Figure 3 shows how the fraction $\nu_e/(\nu_e + \bar{\nu}_e)$ evolves with energy. The increase for charged kaons comes from the forward, associated production of K^+ , which is less affected by the steepening of the spectrum than the K^- . The increase for neutral kaons comes mainly from the K^0 – \bar{K}^0 asymmetry. The $\nu_e/\bar{\nu}_e$ ratio is significantly greater than one and increases with energy. This fact needs to be accounted for in evaluating the atmospheric neutrino

background at all energies.

Several approximations are implicit in Eq. 5, which is a solution of the atmospheric cascade equations in which production of pions and kaons from nucleons are accounted for, but production of kaons by pions is neglected. In the context of a calculation of the inclusive rate of neutrinos from a steep primary spectrum, such a contribution is proportional to a product of two small Z -factors and therefore very small. A potentially more important approximation in the present context is the neglect of transitions from one type of kaon to another. Accounting for the cross terms would require solving a set of matrix equations which would be a generalization of the approach of Ref. [5] to include K_S as well as K_L via production of K^0 and \bar{K}^0 . We have checked the solutions of Ref. [5] that track separately the charge-exchange process $K^+ \leftrightarrow K_L$ to insure that the simpler approximation of Eq. 5 is numerically accurate. We also checked that neglect of the $N \rightarrow \pi^\pm \rightarrow K$ channel leads to changes at the 1% level.

The production of kaons by kaons is included in Eq. 5 through the attenuation lengths for each channel defined by

$$\Lambda_K = \frac{\lambda_K}{1 - Z_{KK}}, \quad (8)$$

where λ_K is the kaon interaction length. The combination in which the attenuation lengths enter the solution of the cascade equations (Eq. 6) is a quantity of order one and does not change much over the range of physically possible values of the attenuation lengths. The asterisk on B_3^* in the term of Eq. 5 for K_L allows for the possibility of suppression of the attenuation length for K_L due to loss to $K_S \rightarrow 2\pi$ as a consequence of kaon regeneration. For example, reducing Z_{KK} by the maximum amount possible (1/2) in the attenuation length for $\Lambda_{K_L} = \lambda_K/(1 - Z_{KK})$ reduces the contribution of K_L to $\nu_e + \bar{\nu}_e$ by no more than 6%.

4. Implications

Previous measurements of the ν_e flux have focused on the energy range below a few TeV [16, 17, 18, 19], so have not been sensitive to the K_S -induced component. However, searches for extra-terrestrial neutrinos that are sensitive to ν_e have focused recently on considerably higher energies [20, 21, 22, 23], and so could be sensitive to the K_S induced component. The signature is an increase in the atmospheric ν_e background with a zenith-angle-dependent

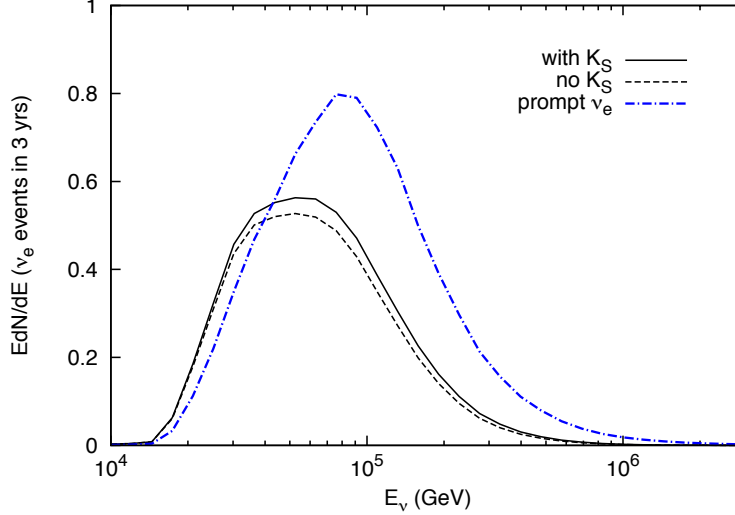


Figure 4: Differential distribution of events induced by atmospheric ν_e in three years of IceCube data with the acceptance as defined in Ref. [21]. The “prompt” contribution is for the charm production model of Ref. [25], modified to take account of the knee in the primary cosmic-ray spectrum.

inflection point (steepening of the slope) at roughly $30 \text{ TeV}/\cos(\theta_Z)$ (see Fig. 1). At energies below or near $\epsilon_{K_S} = 120 \text{ TeV}$, this contribution is nearly isotropic, matching the angular distribution of a prompt atmospheric or diffuse astrophysical flux. In this respect, the angular distribution is similar to that of prompt neutrinos.

In order to quantify this effect, we have used the effective areas published in the supplemental material of Ref. [21] and folded them with the electron neutrino fluxes with and without the K_S contribution. The result is shown in Fig. 4 integrated over the three-year live time of Ref. [22]. The effective areas include absorption in the Earth for neutrinos from below the horizon. We have also included the effect of the neutrino self-veto for events from the Southern sky as calculated in [24]. Adding the contribution from K_S increases the atmospheric ν_e background by 8% (from 0.96 to 1.04 events in 3 years). When the ν_e excess is accounted for in the rate calculation, there is a further increase of 1% arising from the fact that in the 100 TeV range, the charged current neutrino cross section is still $\sim 15\%$ larger than for anti-neutrinos. To put the K_S contribution in context, in the model of Ref. [25]

corrected for the knee in the primary spectrum, the predicted number of ν_e from charm decay to the atmospheric background in the same time interval is 1.48 events.

In the energy range 10-100 TeV, the relative enhancement of the background from the K_S channel is largest in the near-vertical direction, where the conventional atmospheric $\nu_e + \bar{\nu}_e$ flux is the smallest. Between that and the self-veto [24], near-vertical neutrinos have much higher signal (astrophysical ν) to background (atmospheric ν) than near the horizon. In this region, ν from K_S are an important contributor to event-by-event background estimates.

5. Conclusions

We have identified a hitherto overlooked contribution to the conventional atmospheric ν_e flux, from $K_S \rightarrow \pi e \nu$. It is potentially significant at energies above 10 TeV, and, asymptotically, it is nearly equal in magnitude to the components from K_L and K^+ decays. The equality between K_L and K_S components at high energies is independent of the hadronic interaction model that is used to estimate their flux, as long as the two are produced at equal rates. Using a numerical solution of the cascade equations, we have evaluated the magnitude of the K_S contribution and find that in practice it makes a small ($\sim 10\%$) increase in an already small background in recent IceCube analyses aimed at astrophysical neutrinos with energies in the 100 TeV range and above.

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APPENDIX: Numerical approximations for Z-factors

We relate the production Z-factors for neutral kaons in Eq. 5 to the Z-factors for production of charged kaons by assuming that kaon production

by nucleons consists of two components:

(a) associated production in which a valence di-quark in the projectile nucleon picks up an s quark to produce a forward hyperon (Λ or Σ of the appropriate charge) and

(b) production of K - \bar{K} pairs. A K^- cannot be produced in association with a single hyperon, so we make the approximation that K^- is always produced as a member of a kaon pair. As a starting point for calculation of the energy-dependent Z-factors by Eq. 4 we use the numerical values of $Z_{pK^+} = 0.0090$ and $Z_{pK^-} = 0.0028$ tabulated in [3] for a differential spectral index of 2.7. We denote the production Z-factor for associated production by a proton as

$$Z_A = Z_{pK^+} - Z_{pK^-} \approx 0.0062. \quad (9)$$

Writing each channel as a sum of associated production and K^+ - K^- pair production leads to

$$\begin{aligned} Z_{pK^+} &= Z_A + Z_{pK^-} = Z_{nK^0} \approx 0.0090 \\ Z_{nK^+} &= \frac{1}{2} Z_A \frac{r}{r+1} + Z_{pK^-} = Z_{pK^0} \approx 0.00425 \end{aligned} \quad (10)$$

for production of $K^+ = (u\bar{s})$ and $K^0 = (d\bar{s})$. The factor 1/2 in the second line of Eq. 10 comes from quark counting: there are two ways to choose the leading valence di-quark for the processes in the first line, but only one way for those in the second line. The factor r is the ratio of production of one charge state of a Σ hyperon to production of a Λ . For example, to produce a K^+ with an incident neutron in association with a hyperon, the simplest process is $n \rightarrow K^+ + \Sigma^-$, whereas both Λ and Σ^0 contribute to production of K^+ by a proton. Production of Σ is suppressed relative to Λ at least by the squared mass ratio $r = 0.88 = (\Sigma/\Lambda)^2$, which is the value use for the plots. Numerical results are not very sensitive to this assumption. As an example on the low side, we can use the ratio of Σ^0/Λ measured in $e^+e^- \rightarrow$ hadrons, which will be an underestimate because of the absence of the incident baryon. If we take $r = 0.25$ [10] then the flux of K^+ decreases by 2% and the flux of neutral kaons by 8%. The ratio of K_S to K_L remains unchanged.

For production of anti-kaons we take

$$Z_{p\bar{K}^0} = Z_{n\bar{K}^0} = Z_{pK^-} = Z_{nK^-} \approx 0.0028. \quad (11)$$

The approximate numerical values shown here apply at energies below which the knee in the primary spectrum affects the integral in Eq. 4. For energies

$E_\nu > 300$ TeV the magnitude of the Z-factors decrease by approximately a common factor as a result of the steepening of the primary spectrum.

Next we combine the proton and neutron contributions into a single factor that can be multiplied by the total flux of nucleons as in Eq. 5. So, for example, $Z_{NK^+} = f_p Z_{pK^+} + f_n Z_{nK^+}$, etc. We take the fraction of protons as $f_p \approx 0.8$ and the neutron fraction as $f_n \approx 0.2$, appropriate for the model of the primary spectrum we are using [14]. With the numerical values in Eqs. 10,11, this gives $Z_{NK^+} \approx 0.00805$. We therefore estimate

$$\frac{\nu_e}{(\nu_e + \bar{\nu}_e)} = \frac{Z_{NK^+}}{Z_{NK^+} + Z_{NK^-}} \approx 0.74 \quad (12)$$

for neutrinos from decay of charged kaons.

K_L and K_S are orthogonal mixtures of K^0 and \bar{K}^0 with equal weights. Therefore

$$Z_{NK_L} = Z_{NK_S} = \frac{1}{2}(Z_{NK^0} + Z_{N\bar{K}^0}) \approx 0.0040. \quad (13)$$

From Eq. 10, $Z_{NK^0} = f_n Z_{nK^0} + f_p Z_{pK^0} \approx 0.0052$ and $Z_{N\bar{K}^0} \approx 0.0028$. Thus, in the high energy limit where the Ke3 decays reflect the K^0 - \bar{K}^0 asymmetry, the ratio $\nu_e/(\nu_e + \bar{\nu}_e) \approx 0.65$ for neutrinos from decay of neutral kaons. The composite ν_e fraction is shown in Fig. 3.

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